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Resonant tunneling through single thin barrier heterostructure with spacer layers

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At first sight tunneling through single barrier heterostructure is a simple problem solved on first pages of any quantum mechanics textbook. However, undoped spacer layers between a barrier and highly doped contact regions are incorporated usually in real structures to avoid dopants diffusion into barrier materials. The existence of the spacer layers immediately makes the problem of tunneling through a single barrier structure more complicated and many different phenomena could appear to accompany a simple tunneling process. For example, reflection of electrons from highly doped contact regions could give rise to additional tunnel resonances observed in $I-V$ tunnel characteristics [1]. Recently we indicated that residual light doping of a barrier gives rise to extra current around zero external voltage bias due to the appearance of the accumulation layers on both sides of the 5 nm thick barrier and additional resonant tunneling conductance between these build-in two dimensional electron layers [2].

In this work we present tunneling current measurements on the structure with very thin 2.5 nm barrier identical otherwise to used in the previous work [2]. We have found that additional conductance in this structure at zero bias is as large as 25% without magnetic field and reaches 100% in the magnetic field $B = 8$ T parallel to the tunneling current. We argue that build-in accumulation layers transfer the single barrier structure to resonant tunneling triple barrier structure where spacer layers play role of the external barriers. This model at least qualitatively explains all our findings.

The heterostructures used for the fabrication of experimental samples were grown by the MBE on a (100)-oriented Si doped n^+-type GaAs wafer ($N_d = 2 \cdot 10^{18}\,\mathrm{cm}^{-3}$) at the substrate temperature 570°C. The structure consisted (in the order of growth) of a lightly Si-doped, a 50-nm–thick GaAs layer ($N_d = 2 \cdot 10^{16}\,\mathrm{cm}^{-3}$), a 10-nm–thick undoped GaAs layer; a 2.5-nm–thick AlAs barrier layer; a 10-nm–thick undoped GaAs layer; a 50-nm–thick lightly doped GaAs layer ($N_d = 2 \cdot 10^{16}\,\mathrm{cm}^{-3}$); and a 0.4-mm–thick GaAs cap-layer ($N_d = 2 \cdot 10^{18}\,\mathrm{cm}^{-3}$). Ohmic contacts were obtained by successive deposition of AuGa/Ni/Au layers and annealing at $T = 400$°C. A mesa–structure 100 μm in diameter was fabricated by conventional chemical etching.

We measured dependences of current,and differential conductivity dI/dV on a voltage bias in magnetic fields up to 15 T at 4.2 K. The dependence of the differential conductivity dI/dV was measured by lock-in technique.

Figure 1(a) shows the differential tunneling conductance G as a function of bias V_b at various magnetic fields $B \parallel J$ up to 8 T. As can be seen in Fig. 1(a) the conductance peak with the amplitude $\Delta G/G \approx 0.25$ was observed at $B = 0$ T near zero voltage. The conductance peak becomes narrower and its magnitude increases with increasing magnetic field. For

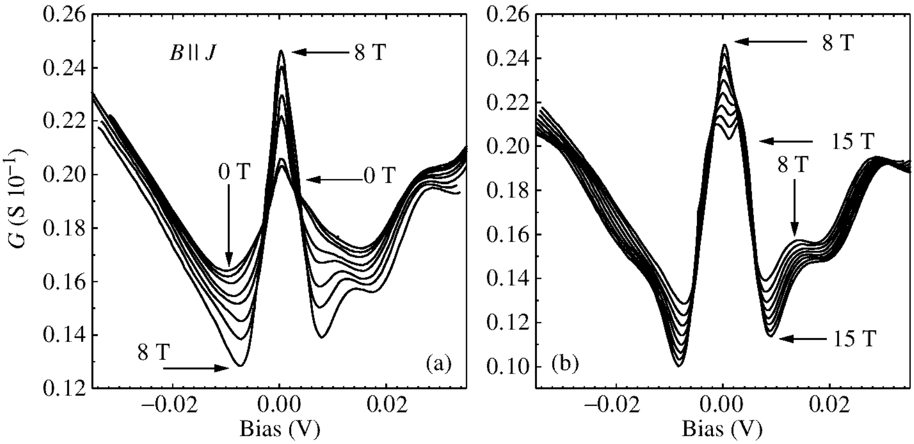

Fig. 1. (a) Tunneling differential conductance as a function of external voltage bias without and in different magnetic fields $B \parallel J$ up to 8 T. Magnetic field step between the curves is 1 T. (b) Tunneling differential conductance as a function of external voltage bias in different magnetic fields $B \parallel J$ from 8 T to 15 T. Magnetic field step between the curves is 1 T.

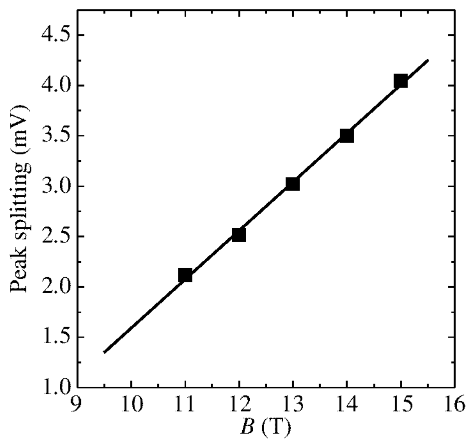

Fig. 2. Magnetic field dependence of the zero bias conductance peak Δ splitting.

higher magnetic fields as can be seen in Fig. 1(b) the magnitude of the conductance peak decreases smoothly with increasing magnetic field from 8 T to 11 T. Then in magnetic field higher then 11 T a dip around zero bias appears in the $G(V_b)$ characteristics. With increasing magnetic field both the depth of the dip and the separation of the surrounding peaks become larger. Thus over the range of magnetic field from 11 T to 15 T the conductance peak splits. The magnetic field dependence of the conductance peak splitting Δ are shown in Fig. 2, that is voltage separation between small conductance peaks around zero voltage. The the peak splitting increases linearly with magnetic field increase. Taking into account the leverage factor in the structure, $\Delta(B)$ dependence are described by the expression $\Delta \approx 0.15\hbar\omega_c$.

Figure 3 shows the experimental conductance characteristics $G(V_b)$ at various magnetic fields $B \perp J$ up to 8 T. The conductance peak decrease with increasing magnetic field and disappears at $B \approx 4$ T. With further increase of magnetic field the conductance at zero bias

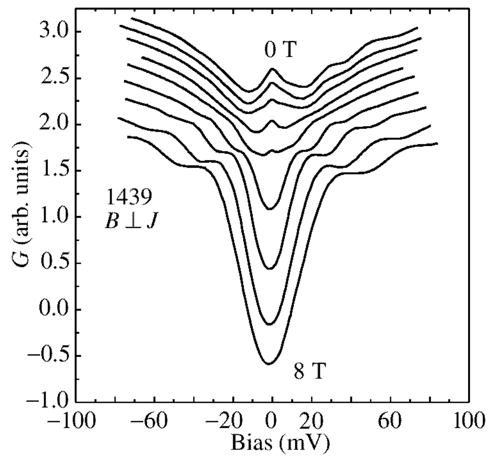

Fig. 3. Tunneling differential conductance as a function of external voltage bias without and in different magnetic fields $B \perp J$ up to 8 T. Magnetic field step between the curves is 1 T. The curves are shifted vertically for clarity.

rapidly falls down.

As was mentioned above all the observed features are typical for triple barrier structure in resonance at zero bias voltage bias. Increase of the tunnel conductance with parallel to the current magnetic field higher then 4 T and following decrease reflects the density of states at the Fermi level when only last Landau level is occupied in the accumulation layers. The splitting of conductance peak around zero bias in a magnetic field higher 11 T is due to the suppression of tunneling current between 3D and 2D states first observed by Ashoori *at al.* [3]. The suppression of tunnel conductance by in-plane magnetic field is typical for 2D–2D tunneling processes [4].

Thus we have studied the tunneling in a single thin barrier heterostructure with spacer layers. All findings are explained in terms of resonant tunneling through triple barrier structure.

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